THE ECONOMIC EFFECT OF PULSE REPETITION RATE ON THE SIZE, WEIGHT, AND COST OF RADAR MODULATORS

Richard Mansfield Romley
and
Wilbur Harry Sample

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MODULATORS

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Submitted in partial fulfillment of the requirements

for the degree of Naval Engineer

at the

Massachusetts Institute of Technology

May 1954

Cambridge, Massachusetts
May 24, 1954

Professor L. F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Professor Hamilton:

In accordance with the requirements for the degree of Naval Engineer, we submit herewith a thesis entitled " The Economic Effect of Pulse Repetition Rate on the Size, Weight, and Cost of Radar Modulators."

Respectfully,

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ABSTRACT

The purpose of this investigation was to establish the economic effect of increasing the pulse repetition rate upon the size, weight, and cost of radar modulators. Three line-type circuits with repetition frequencies of 400, 2,000, and 10,000 were designed. The size, weight, and cost of the principal components were determined by reference to manufacturers' manuals and catalogues and by consulting design engineers of firms in the area. For the three modulators considered, size (volume), weight, and cost figures in order of ascending pulse repetition rates, i.e., 400, 2kc, and 10kc, are: volume in cubic inches - 248.20, 96.07, 176.06; weight in pounds - 14.44, 6.975, 7.1; cost in dollars - 132.08, 105.38, 232.33. These figures include only the principal components of the modulator; i.e., charging reactor, switch tube, pulse-forming network, shunt diode, and shunt resistor. Additional items such as chassis, various wiring circuits, pulse transformer, tube sockets, and labor costs have been omitted in the data, but their influence is discussed. It is concluded that an increase in pulse repetition rate may result in a decrease in the size and weight of the radar modulator. If the modulators were actually under construction, the cost differential may be such as to be of little significance.

Thesis Supervisor: Peter Elias

Title: Assistant Professor of Electrical Engineering

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INTRODUCTION

The object of this thesis is to ascertain the effect of varying the pulse repetition rate upon the size, weight, and cost of radar modulators. It was believed that through the means of changing the repetition rate to higher value, a modulator of less weight and smaller size could be developed. The trend of cost, however, was more questionable. The work that follows was made in order to establish just what economic trend would appear.

The radar modulator is the heart of the radar system. The pulser, another title for the modulator, controls the operation of the transmitter. The function of the modulator is to deliver power to the transmitter in pulses of satisfactory shape, duration, and repetition frequency. Fed into the magnetron of the transmitter, these power-packed pulses emanate as radio frequency energy. The modulator, therefore, can be considered the keyer of the radar system.

Since we are interested in establishing a trend in the size, weight and cost of radar modulators with increasing pulse rate, we have arbitrarily selected pulse duration and average power to be constant. To hold average power constant is reasonable since in any installation, particularly aircraft, the radar manufacturer has a fixed power supply which he must use. He must remain within the power limitations. Otherwise, each new radar system would require

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One must consider the radar range equation to evaluate the effect of holding average power constant. The range equation may be expressed as follows:

$$R_{max} = \frac{1}{2\sqrt{\pi}} \left[P_t \tau x \frac{1}{S_{min}} x\, G_t A_r x A_o \right]^{\frac{1}{4}} \qquad (1)$$

where P_t is the pulse power output, τ is the pulse duration, S_{min} is the minimum detectable echo pulse energy, $G_t A_r$ is the characteristic of the antenna, and A_o is the reflecting effectiveness of the object. For purposes of comparison it is assumed that the characteristics of the antenna and the reflectivity of the object remain unchanged. Noting that the peak power equals the average power divided by the duty ratio, and making this substitution, the range equation takes the following form:

$$R_{max} = \left(\frac{K}{f_r S_{min}}\right)^{\frac{1}{4}} \quad \text{since } P_{ave} \text{ is constant.} \qquad (2)$$

We now have reduced the equation to the point where the range is inversely proportional to the fourth root of the pulse repetition rate and the minimum detectable energy. One might question the advisability of going to higher pulse rates since it appears that

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Consider now the echo pulse energy. If it is assumed that the means of presentation is an "A" scope, then this energy will produce a deflection of the trace. If the signal is strong, there will be no difficulty in detecting the deflection above the noise background. As the signal gets weaker and weaker, the deflection will eventually subside into this background of noise, or "grass" as it is commonly called. The minimum detectable echo pulse energy is that amount which will produce a pulse just detectable above the noise. The absolute value of the minimum energy is a difficult quantity to calculate because it depends upon so many factors. To list a few: the i-f bandwidth, video bandwidth, pulse duration, sweep speed, scan rate, etc.

If one had to rely upon the random appearance of a signal above the noise in every single sweep,it would be extremely difficult to distinguish the signal peak which might be exceeded by noise peaks in some intervals. If, however, it were possible to average several sweeps, it would be easier to detect the signal above the noise. This is because the signal peak, consisting of signal plus noise, would not be essentially altered while the noise level has been reduced. It would be extremely unlikely that the random fluctuations of the noise any increase in the pulse frequency will have an adverse effect upon the range. We have said nothing about the minimum detectable echo pulse energy yet.

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The results of these tests have shown that

$$\frac{S_1}{S_2} \cong \left[\frac{fr_2}{fr_1}\right]^{\frac{1}{2}} \tag{3}$$

Now, if we take the ratio of the maximum range for two different pulse rates, we see that

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and if we substitute equation (3) into equation (4), the range equations reduces to

$$\frac{R_1}{R_2} \cong \left[\frac{fr_2}{fr_1}\right]^{\frac{1}{8}} \tag{5}$$

Considering only equation (4), we might have expected that the pulse repetition rate need change by a factor of 16 to change the ratio of the ranges by a factor of 2. But having seen how the minimum detectable energy varies with pulse repetition rate, it is now apparent that the pulse rate must change by a factor of 256 in peaks would occur in the same place on the trace. The average of several sweeps has the effect of reducing the peaks to some nearly average value. This is essentially an integration process which could be accomplished mechanically but is unnecessary because the eye performs this task exceedingly well. In a series of tests, described in Section 8.2 of Reference (3), the signal to noise ratio was adjusted until a group of observers, using an A-scope, could correctly identify the signal from the noise nine out of ten times.

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Let us now briefly review the types of modulator circuits in use. We shall consider them in a general manner only. For more detail, the reader is referred to the bibliography, references (2) and (4).

With the exception of special cases most of the pulsers of today make use of the electrostatic means of energy storage. Capacitors or pulse-forming networks are the two elements used for this purpose. Figure I shows the block diagram for the basic circuit utilizing energy storage by the above mentioned method.

In this circuit, the supply voltage charges up the energy storing element during the interval between pulses. During this time the switch is open. The power supply, isolating element, energy storage element, and load form the charging loop. To create the pulse, the switch is closed; thus, the discharge circuit becomes the right-hand loop of Figure I. During the latter period, the isolating element serves to prevent excessive power being drawn from the supply.

Two types of modulators can be developed from the basic circuit. One, the hard-tube pulser, makes use of a capacitor as the energy storage element. The block diagram is shown in Figure II. In the hard-tube modulator, the switch must interrupt the current in the order to change the ratio of the ranges by 2. From the previous analysis, it can be seen that holding average power constant is detrimental to the range but not nearly as much as might have been expected initially.

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The line-type modulator is the second and simpler type. It relies on a pulse-forming network as the energy storage element. This same network also shapes the pulse. In other words, the pulse-forming network stores the amount of energy required for the pulse; then, the discharge circuit forms the pulse as it carries out its task. No driver circuit is needed as in the hard-tube pulser. A trigger voltage into the switch tube controls the pulse frequency. The open-end, artificial transmission line type of pulse-forming network is most frequently used when a pulse of excellent rectangular shape is wanted. The switch may be any one of the following: rotary spark gap, "trigatron", series gap, hydrogen thyratron, or mercury thyratron. Which one used in a particular circuit depends upon that circuit and its requirements. The isolation element in this type pulser is usually an inductance. Inductance charging is used because of its high efficiency and because it permits charging the pulse-forming network to a voltage approximately twice that of the power discharge circuit at the proper time. To do this, a driver circuit connected to the grid of the switch tube is necessary. The driver circuit is required to shape the pulse, to set the pulse repetition rate, and to maintain accurate pulse spacing. An example is the line-controlled blocking oscillator driver. The switch tube must be capable of carrying efficiently the large pulse currents required. A high-power switch tube frequently used is the 715-B. The isolating element may be an inductor or a resistor or both.

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The two types of modulator circuits have their advantages and disadvantages. The line-type pulser has a high efficiency, while that of the hard-tube type is low. The latter pulser does give somewhat better rectangular pulses. Pulse duration changes in the hard-tube pulser are more easily accomplished because the switching is done in the low voltage circuit. The line-type pulser, however, does have a simpler circuit. This leads to easier servicing and to smaller size and less weight. These last two factors are very important in many cases.

In the preceding discussion we have not taken into consideration the complete modulator. We have dealt only with the main components. Wiring, warm-up circuits, relay circuits, overload circuits, and switching circuits have been omitted. Because all modulators require such circuits and because of the detail involved, they have not been included in the modulators investigated. Let us, however, look for a moment at the load of the circuit. The load is a magnetron. Since it is desired to match the load to the pulse-forming network in a supply. In this case, the isolation element is required to prevent the high voltage charge on the pulse-forming network from short-circuiting the supply each time the network discharges. The inductance also serves to slow down the rate of charging. The power supply may be either d-c or a-c depending upon the type of charging preferred in the particular circuit involved.

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FIGURE I

BASIC CIRCUIT FOR MODULATOR UTILIZING ELECTROSTATIC ENERGY STORAGE

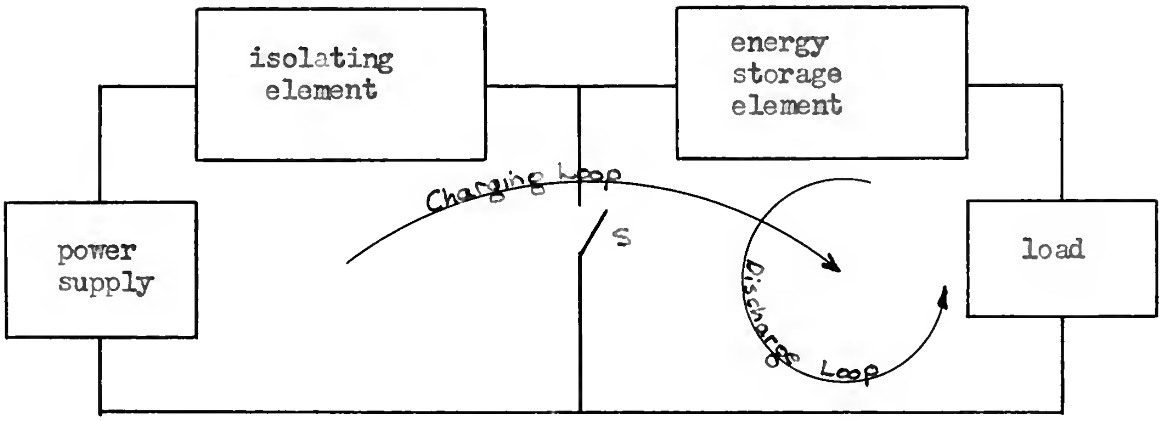


FIGURE II

BASIC CIRCUIT FOR HARD-TUBE MODULATOR CIRCUIT

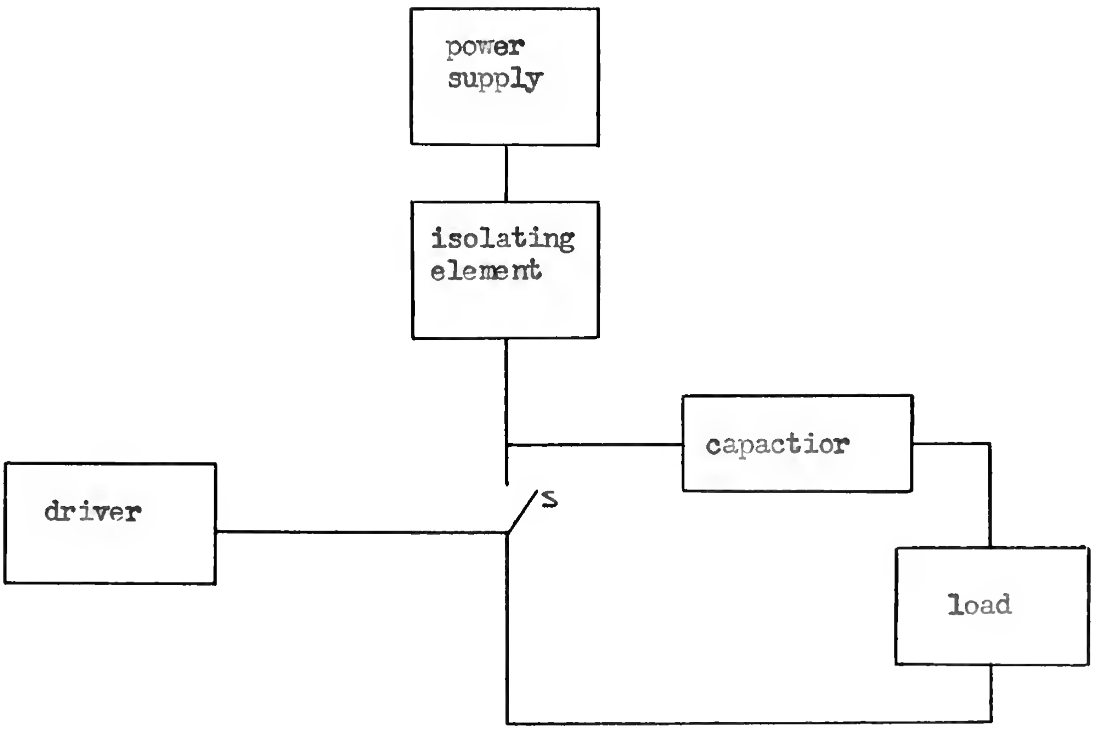


FIGURE I

BASIC CIRCUIT FO[illegible] UTILIZING [illegible]

ENERGY STORAGE

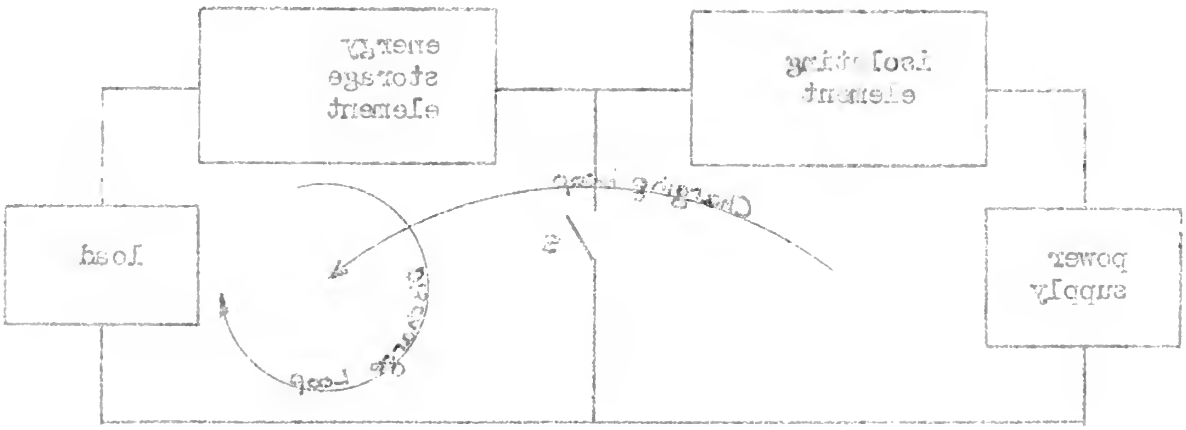


FIGURE II

BASIC CIRCUIT FOR HARD-TUBE MODULATOR CIRCUIT

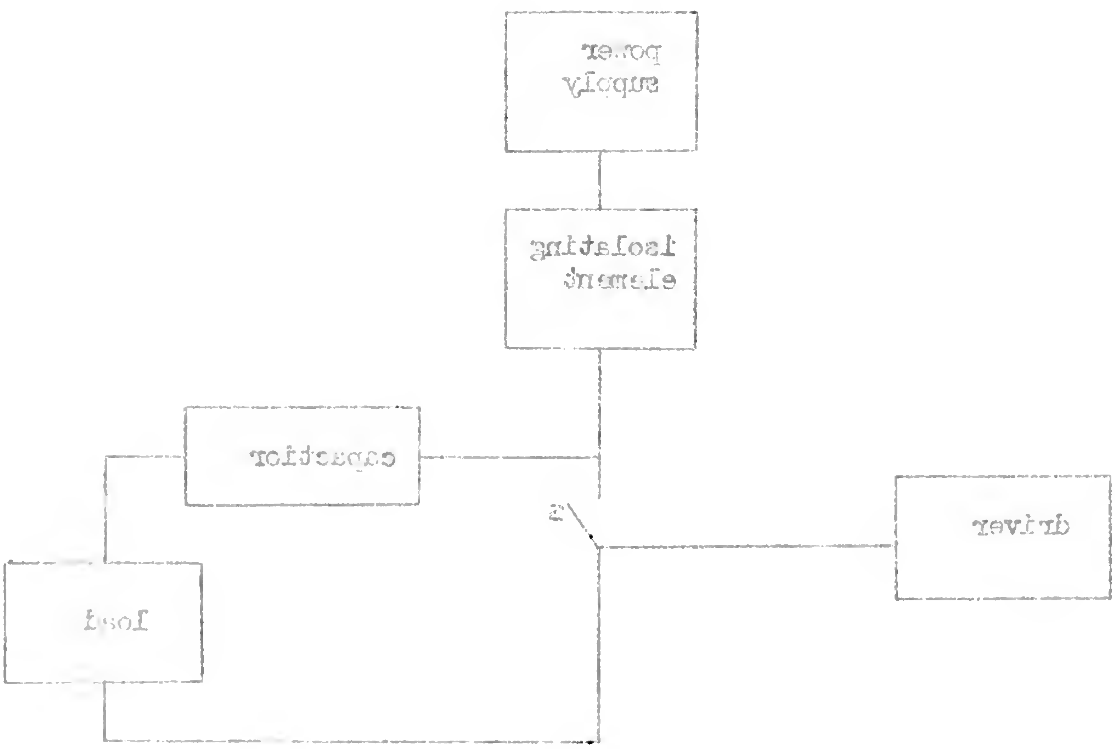


FIGURE III

BLOCK DIAGRAM OF LINE-TYPE MODULATOR

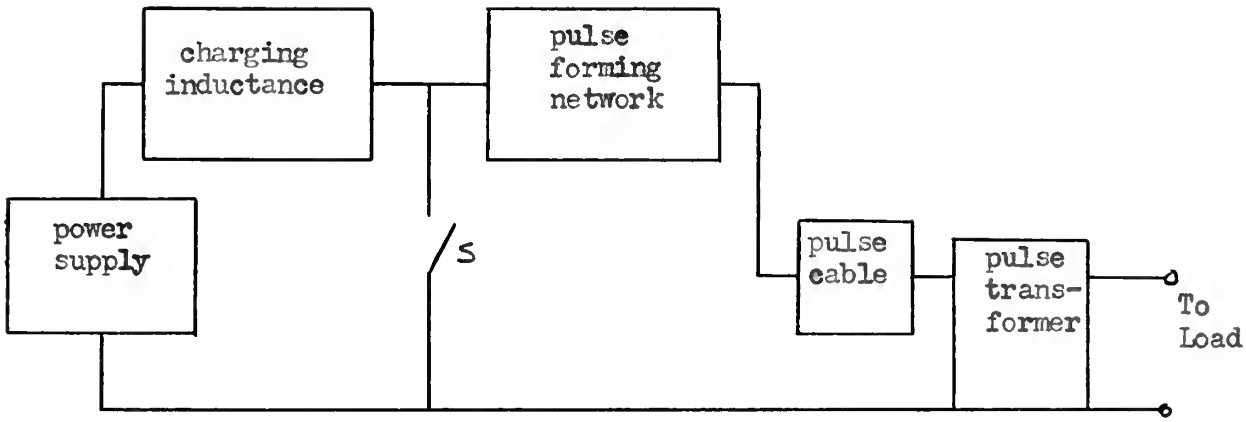
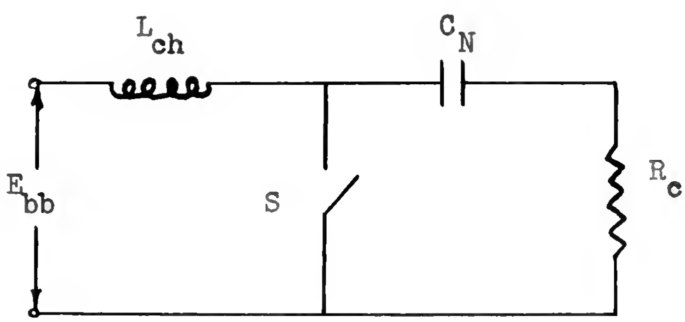


FIGURE IV

EQUIVALENT CIRCUIT



PROCEDURE

It was considered that the pulse repetition rate might have an effect on the size, weight, and cost of radar modulators. It was decided to use the line-type pulser in preference to the hard-tube type, but several factors had to be considered in making this choice.

A comparison of the two types of pulsers reveals that the line-type is more efficient, particularly at high pulse power outputs; requires a lower supply voltage with inductance charging; and the circuit is much simpler, permitting a smaller and lighter modulator. Secondly, a modulator of the line-type has been designed and built to operate at a 10kc pulse repetition rate. Finally, it was considered that there would be no significant change in size, weight, and cost if the hard-tube type pulser were used because the driver part of the circuit would remain unchanged. The storage capacitor and switch tube would represent the primary changes.

It was then determined which factors to hold constant as previously discussed. An attempt was made to use the same magnetron at all pulse rates. This proved to be unfeasible since magnetrons are designed for specific pulse rates and peak power requirements. For this reason, it became necessary to choose a different magnetron for each pulser.

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The equivalent circuit which is used for the analysis is shown in Figure IV. Consider first the discharge circuit which consists principally of the pulse-forming network, a hydrogen thyratron, and a load. It is advantageous from the point of view of simplicity to start the analysis at the load and work back through the circuit. The load for all the pulse repetition rates is the magnetron. If the operating point of the magnetron is known, the static resistance is

$$R_{static} = \frac{E}{I} \tag{6}$$

where E and I are the operating voltage and current respectively.

Impedance matching is very important in the design of a line-type pulser because of its effect upon the utilization of the stored energy and the pulse shape. In practical installations the magnetron is remote from the load. The optimum transfer of power will occur when the load matches the impedance of the pulse-forming network. The output of the pulser is usually fed into a coaxial cable which connects to the primary of the pulse transformer. The pulse transformer effectively matches the load to the pulse cable which in turn is matched to the impedance of the pulse-forming network. The cable commonly used for this purpose in the United States has an impedance of 50 ohms.

It is now possible to calculate the equivalent capacitance of the pulse-forming network knowing the characteristic impedance, 50 ohms, and the pulse duration, 1 microsecond. If it is assumed

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It is now possible to calculate the equivalent capacitance of the pulse-forming network knowing the characteristic impedance, 50 ohms, and the pulse duration, 1 microsecond. If it is assumed that the lossless network is charged to some voltage, E_{st}, and then discharged into its characteristic impedance, the energy originally stored in the capacitance, C_N, is delivered to the load resistance. Expressing this in the form of an equation, we have

$$\frac{1}{2} C_N E_{st}^2 = \left(\frac{E_{st}}{2}\right)\left(\frac{E_{st}}{2R_c}\right)\tau \qquad (7)$$

where τ is the pulse duration, and R_c is the load resistance which equals the characteristic impedance. Solving equation (7) for C_N, we obtain

$$C_N = \frac{\tau}{2R_c} \qquad (8)$$

Inductance charging, which is almost exclusively used in microwave radar, has been assumed because it provides better isolation between the switch and the power supply and is more efficient than resistance charging. Furthermore, it was assumed that resonant charging would be used. The charging process begins with the capacitance initially uncharged. Because the resistance in the series L-C circuit is low, the voltage across the capacitance oscillates sinusoidally. During any cycle, the charging voltage reaches a maximum which is approximately 1.9 times the supply voltage. At the time the voltage reaches this maximum, the current through the inductance is zero. The following equations illustrate this point. For d-c resonant charging with matched load the equations take the following form:

$$i_{ch}(t) = \frac{E_{bb}}{\omega L_{ch}} \varepsilon^{-at} \sin \omega t \tag{9}$$

where $a = \frac{R_c}{2L_{ch}}$, $\omega_o^2 = \frac{1}{L_{ch}C_N}$, and $\omega^2 = \omega_o^2 - a^2$.

$$v_N(t) = E_{bb} + E_{bb}\varepsilon^{-at}\left(\cos\omega t + \frac{a}{\omega}\sin\omega t\right) \tag{10}$$

For resonant charging $\omega T_r = \pi$. $v_N(t)$ is maximum when $T = T_r$; therefore, since $\omega T_r = \pi$, $i_{ch}(t)$ must equal zero.

If the switch is closed at this instant, a voltage pulse of amplitude $\frac{E_{st}}{2}$ will appear across the load. With d-c resonant charging, the value of the charging inductance necessary can be determined from the following expression

$$L_{ch} = \frac{1}{\pi^2 f_r^2 C_N} \tag{11}$$

Use was made of all these equations in the analysis of the circuits. For details of the calculation, see Appendix B.

The quantities determined above, peak and average currents, peak charging wave voltage on the pulse-forming network, and the d-c supply voltage, are all necessary to the design of the charging reactor and the pulse-forming network as well as the selection of a hydrogen thyratron. In order to determine the size, weight, and cost of these components, trade catalogues, sales representatives, and manufacturers were consulted.

RESULTS

The results of the investigation are presented in the following table. The modulators considered are listed by the pulse repetition rates; i.e., as 10Kc, and 2 Kc, and 400. The volume is given in cubic inches, the weight in pounds, and the cost in dollars and cents.

TABLE I

Summation of Size, Weight, and Cost

For Each of The Modulators

Component	Modulator 400	2Kc	10Kc
Size (Volume)(cu.in.)			
Charging Reactor	141.00	11.87	9.66
Switch Tube	43.00	32.90	88.30+
Pulse-Forming Network	58.70	45.80	72.60
Shunt Diode	5.15	5.15	5.15
Shunt Resistor	0.35	0.35	0.35
Total	248.20	96.07	176.06+
Weight (pounds)			
Charging Reactor	10.50	3.0	1.0
Switch Tube	0.59	0.625	1.5+
Pulse-Forming Network	2.75	2.75	4.0
Shunt Diode	0.5	0.5	0.5
Shunt Resistor	0.1	0.1	0.1
Total	14.44	6.975	7.1+
Cost			
Charging Reactor	$36.00	$19.00	$14.00
Switch Tube	42.75	33.05	150.00+
Pulse-Forming Network	35.00	35.00	50.00
Shunt Diode	18.00	18.00	18.00
Shunt Resistor	.33	.33	.33
Total	$ 132.08	$ 105.38	232.33+

\+ For explanation and alternative see Discussion

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Summation of Size, Weight, and Cost

For Each of The Modulators

Component	Modulator 400	2Kc	10Kc
Size (Volume)(cu. in.)			
Charging Reactor	111.00	11.87	9.66
Switch Tube	43.00	32.70	88.30+
Pulse-Forming Network	58.70	45.80	72.50
Shunt Diode	5.15	5.15	5.15
Shunt Resistor	0.35	0.35	0.35
Total	218.20	95.77	176.06+
Weight (pounds)			
Charging Reactor	10.50	3.0	1.0
Switch Tube	0.59	0.625	1.5+
Pulse-Forming Network	2.75	2.75	0.4
Shunt Diode	0.5	0.5	0.5
Shunt Resistor	0.1	0.1	0.1
Total	14.44	6.975	7.1+
Cost			
Charging Reactor	$36.00	$19.00	$14.00
Switch Tube	42.75	33.05	150.00+
Pulse-Forming Network	35.00	35.00	50.00
Shunt Diode	18.00	18.00	18.00
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Total	$ 132.08	$ 105.38	232.33+

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DISCUSSION

Before considering the results of the investigation, let us discuss the scope of the table. Only the main components of the modulator were used for determining the size, weight, and cost of a unit because these components are the parts of the modulator which change as the pulse repetition rate is varied. The wiring, warm-up circuits, overload relays, and various other auxiliary circuits would be necessary in all modulators and would not be altered to the extent where they need be considered. Also, great detail of design would be encountered if these circuits were included in the investigation. No determination of component spacing for insulation purposes was made. In this regard, it was assumed that since the peak voltages appearing in the modulator circuits varied inversely as the pulse repetition rate (the 10Kc modulator having the smallest peak voltage), the insulation spacing would tend to decrease as the pulse frequency increased. Thus, looking at Table I, the 400 modulator has the largest volume. Since this modulator also carries the highest voltage, the insulation spacing would tend to increase the volume size. Also, some spacing is required because of the shape and necessary position of the components. As a result of the foregoing, it was decided to use the volume occupied by the main components for size comparison.

Another assumption was made for the cooling of the modulator. Forced air cooling with an ambient temperature of 90°C. was assumed

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Another assumption was made for the cooling of the modulator. Forced air cooling with an ambient temperature of 90°C. was assumed for design purposes. The cooling system was not considered as one of the components of the modulator. Depending upon the installation, various systems of cooling are used. One modulator may have an individual blower. Another pulser may be cooled by means of forced air delivered from a central fan located elsewhere in the installation. For the purpose of the investigation, it was assumed that the modulator cooling systems would be essentially the same and could, therefore, be ignored.

Now let us analyze the results of the investigation. From Table I it is obvious that the 2Kc modulator, which has a volume of 96.07 cubic inches, is the smallest. The 10Kc pulser stands next in size with a volume of 176.06 cubic inches, and the 248.20 cubic inches occupied by the 400 modulator is by far the largest volume. This would seem to indicate that a medium repetition frequency is advantageous for size considerations. Looking at the individual components reveals that the size of the charging reactor decreases as the pulse repetition rate increases. The switch tubes and the pulse forming networks follow the same trend. Both have the least volume at the 2Kc frequency and are largest at the 10Kc repetition rate.

The 14.44 pounds of the 400 modulator is twice the weight of either of the other two modulators. The 2Kc, the lightest pulser, at 6.975 pounds and the 10Kc at 7.1 pounds are very close in weight.

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The neglected cooling components, wiring circuits, and insulation spacing could be of deciding value between these units. The weight of the charging reactor decreases, and the weight of the switch tube increases as the pulse repetition rate increases. The weight of the pulse-forming network remains the same at 400 and 2Kc, but it increases about 45% at 10Kc.

The cost group of Table I reveals that the 10Kc pulser is the most expensive. The main components would cost $232.33, as compared to $105.38 for the 2Kc modulator and $132.08 for the 400 pulser. Here again, the 2Kc holds the lowest figure. As the repetition frequency increases, the cost of the charging reactor decreases. The cost of the switch tube for the 10Kc modulator is approximately 65% of the total cost and is the costliest of the three. The 400 pulser switch tube is the next most expensive, and the 2Kc tube is the least costly. The price of the pulse-forming network follows the same trend as the weight, differing only in the 10Kc modulator where it increased.

The column totals of the groups of Table I show that the size, weight, and cost tend to decrease when the repetition rate increases from 400 to 2Kc. From 2Kc to 10Kc these factors tend to increase with the repetition rate. The weight increase from 2Kc to 10Kc, however, is slight. The results indicate that the best region of operation for size, weight, and cost considerations is the 2Kc

The neglected cooling components, wiring circuits, and insulation spacing could be of doubtful value between these units. The weight of the charging reactor decreases, and the weight of the switch tube increases as the pulse repetition rate increases. The weight of the pulse-forming network remains the same at 400 and 2Kc, but it increases about 45% at 10Kc.

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It is to be noted in Table I that the pulse-forming network is greatest in size, weight, and cost at the 10Kc repetition rate. At first glance, this would seem to be in error, for the charging voltage of this particular network is the lowest, only 2.2KV. But in this circuit, the average current and, thus, the dissipation losses are higher than in the other networks. The larger case is needed primarily to facilitate the dissipation of the losses as heat. The 400 and 2Kc networks, having less losses, are smaller. Although the two are estimated to be of the same weight and cost, the 2Kc is slightly larger in volume because of slightly higher dissipation losses.

The switch tube of the 10Kc modulator circuit is a tentative selection. Two 4C35 hydrogen thyratrons in parallel were used in the line-type 10Kc modulator actually constructed and operated. It was decided to replace these with a single tube if possible. The one used, the 5949/1907, is a new tube. In fact, it is the first of a series of new thyratrons. With its ability to carry an average current of 500 milliamperes, this tube can easily handle the 220 milliampere current of the 10Kc modulator. The peak ratings for sector. Decreasing the pulse repetition rate from this level leads to great increases in size and weight and a moderate increase in cost. With an increase of repetition frequency above 2Kc, the cost and size become much greater, but the weight remains approximately the same.

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The results of the investigation indicate that the weight is the only factor which does tend to decrease as the pulse repetition rate increases over the range considered. The size and cost decrease to a low point at the middle repetition frequency and then increase again at the high range. Figure V graphically demonstrates the trend of size, weight, and cost of the modulator as the pulse repetition rate varies. This plot is for the pulser components selected originally. It does not include the possibility of a smaller voltages and currents are far above those encountered in the circuit, but the selection was made for the basis of representation. With development progressing as it is, a thyratron which will more efficiently meet the requirements of the 10Kc modulator will be designed. This tube furnishes data which is subject to change. Perhaps something more nearly like the 1035 will be constructed. Should this happen, the following changes would be made in the 10Kc column of Table I: the total volume would be reduced by 55.4 cubic inches, or to 120.66 cubic inches; the weight would become 6.225 pounds instead of the present 7.1 pounds; and the cost would decrease from $232.33 to $115.38. This would substantiate the trend of the weight to decrease as the repetition frequency increased. The size and cost, however, still are greater than those of the 2Kc pulser; but the increases are much less. An increase of 24.59 cubic inches in volume and $10.00 in cost would exist. In the complete modulator, these differences could possibly disappear.

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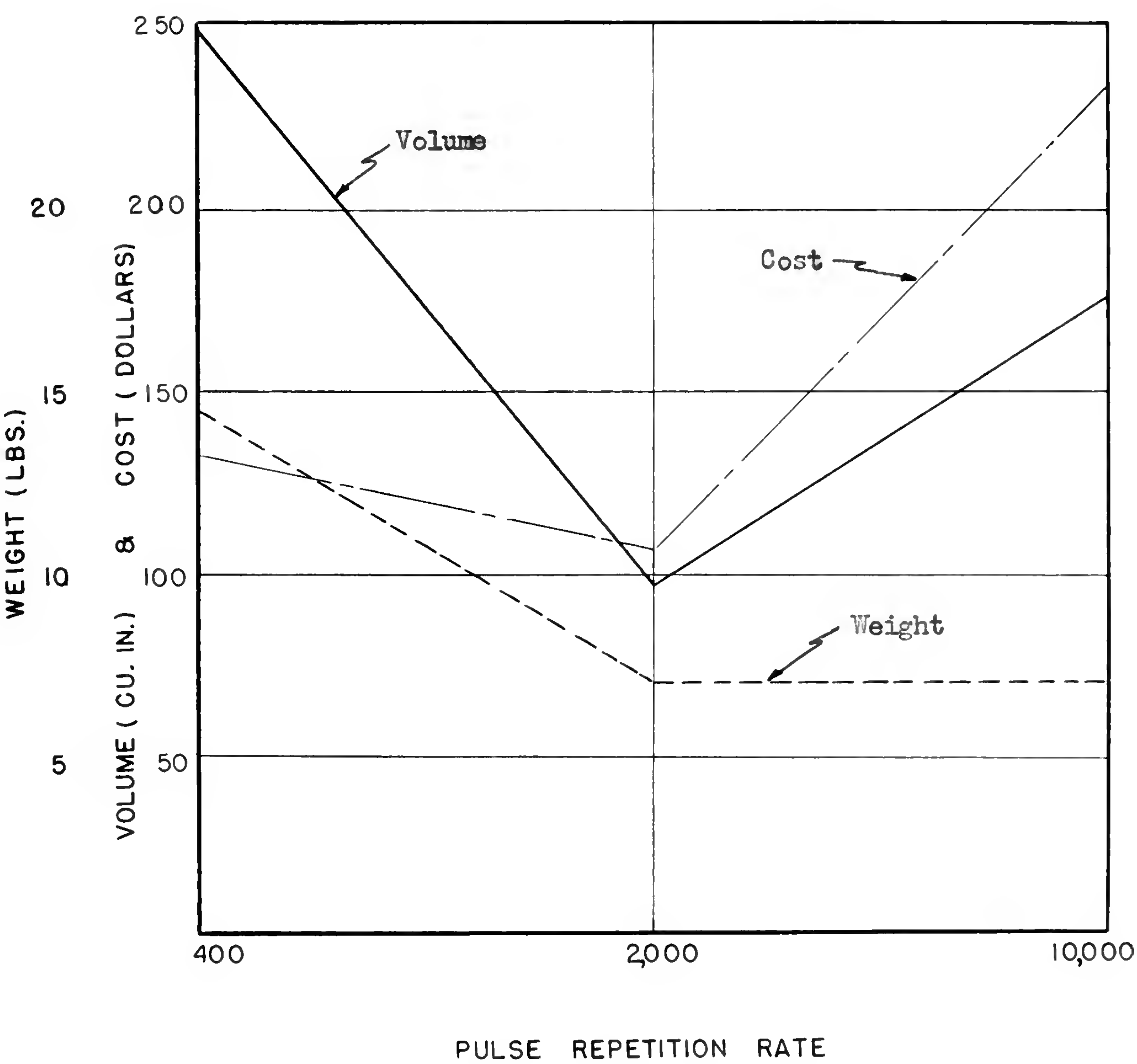
FIGURE V

Plot of Volume, Weight, and Cost

versus

Pulse Repetition Rate

Note: The lines joining points are for the purpose of illustrating trend only. They cannot be used to obtain values between the plotted pulse repetition rates.



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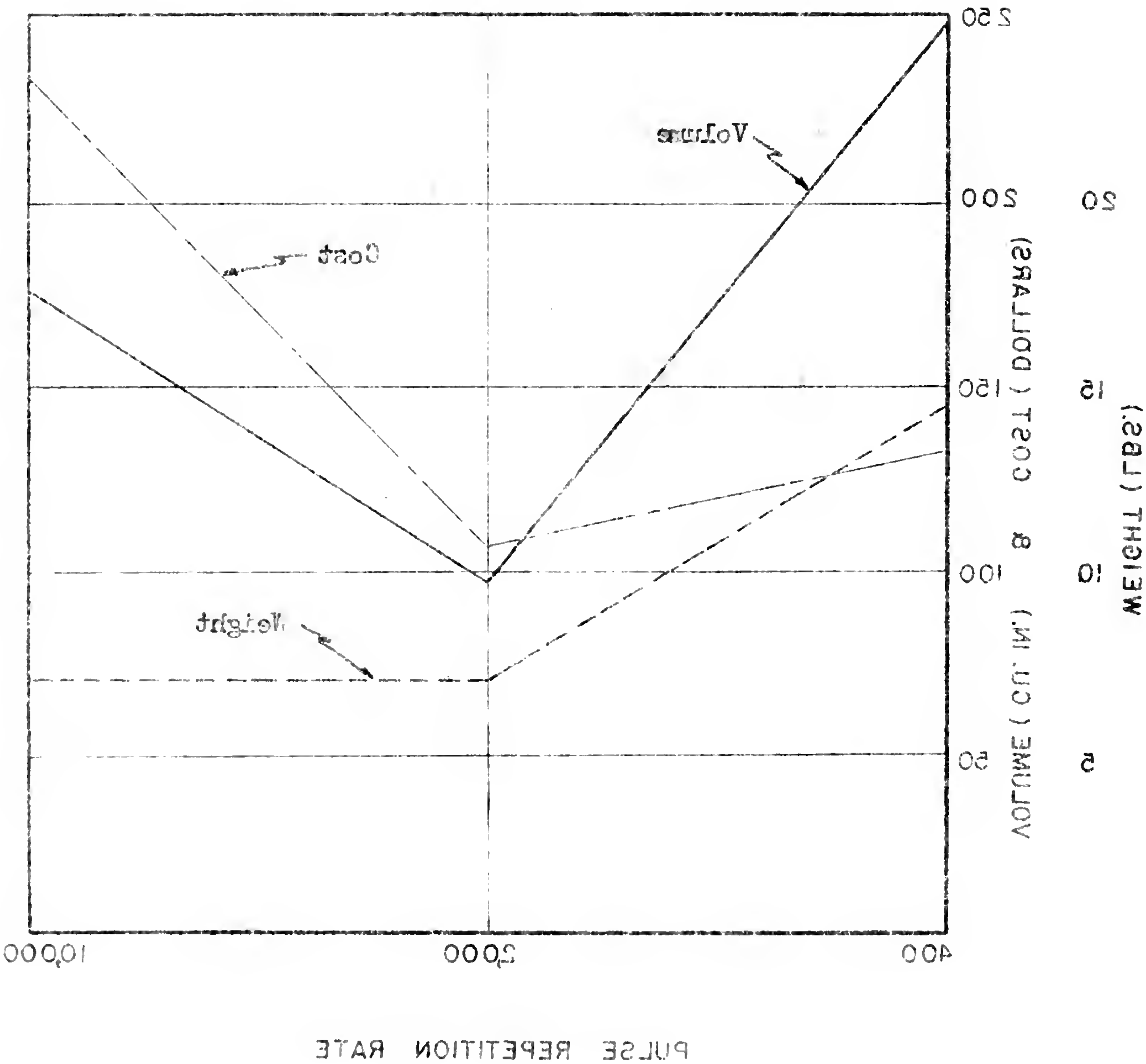

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One other consideration should be mentioned, for it may have a decisive effect for a complete radar installation. In the line-type modulator utilizing inductance charging, the power supply voltage required decreases as the pulse repetition rate increases. To illustrate this, the power supply voltage required for the 400 modulator is 6.21 KV; for the 2Kc, 3.09 KV; and for the 10Kc, 1.22 KV. It would seem that such changes in voltage would make possible similar changes in the unit supplying the voltage. Smaller voltages require smaller generating units and, therefore, less overall size, weight, and cost of the complete installation.

More general and overall views can be derived from the fact that the maximum voltages decrease in the circuit as the repetition rate increases. As mentioned earlier, the insulation spacing requirements will decrease as the maximum voltages decrease. This trend will also hold true in stand-off requirements. With these space-taking factors lessening, the volume of the high repetition frequency modulator will be reduced. Looking at the voltage differences again, one can see that this reduction may be considerable.

The pulse cable, pulse transformer, magnetron ,sockets, and chassis were omitted in the investigation. As was stated in the Introduction, the first three items were not considered as components of the modulator proper. The sockets and chassis were excluded altogether, for it was assumed that their size, weight, and cost would switch tube in the 10Kc circuit as discussed above.

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The total manufacturing cost of this piece of equipment would not be complete without the price of labor. This quantity can be only roughly predicted at this point. It would seem that labor costs would increase slightly for the higher pulse rates. This belief is held because the whole modulator unit becomes smaller and is, therefore, more difficult to construct due to space restrictions.

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Evaluation of the results of the investigation modified by the above discussion seems to indicate that the size and the weight of a radar modulator may decrease as the repetition rate is increased. Cost is even more ambiguous. Integrating the cost fluctuations discussed with the consideration of quantity production of individual components, as well as modulators, leads to great confusion. However, it may be that the pulse repetition rate used will cause only negligible variations in the total modulator cost.

In the evaluation of this investigation, it must be remembered that the factors are based on the present items available at their present prices. Future developments will have their effect on the components with respect to size, weight, and cost. This will be reflected in the physical characteristics of the modulator.

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CONCLUSIONS

The following conclusions are developed from the investigation, but are pertinent only so far as the main components are concerned. These are the pulse-forming network, the charging reactor, the hydrogen thyratron, the shunt diode, and the shunt resistor. Such items as wiring, warm-up circuits, overload relays, and pulse transformers are not considered.

1. The size of the radar modulator tends to decrease at first as pulse repetition rate increases but then increases at the highest rate. This may indicate there is some intermediate frequency at which a modulator of minimum size could be constructed. As noted previously in the discussion, peak voltages decrease with increasing pulse rate. This would probably result in smaller stand-offs, chassis, pulse transformer, and pulse cable as the pulse rate increases. Coupling these with the improved design of a pulse-forming network and thyratron, it is very possible that a 10Kc pulse rate modulator actually constructed might be considerably smaller, relatively, than is indicated in the results.

2. The weight of the pulser tends to decrease at first as the pulse repetition rate increases and then remains nearly unchanged at the 10Kc pulse rate. In conjunction with the statements of item (1), since these auxiliary components are smaller, they would probably be lighter. The effect of this over-all contribution might be to continue the downward trend.

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3. The cost of the modulator is perhaps the most difficult to evaluate. All cost figures are representative of today's prices. Some of the higher prices reflect that the demand for these components are not very great. In particular, the hydrogen thyratron used in the 10Kc modulator is over $100 more than the thyratrons used in the other modulators. If high pulse repetition rates become the rule rather than the exception, this thyratron would probably become competitive in price with the others since the demand would be greater. As in items (1) and (2), other auxiliary components requiring smaller ratings might cost less. Although the authors hesitate to make any concrete conclusions in this respect, it might be that the cost differential from one modulator to the next is small enough so as to be of little consequence if the modulator were actually under construction.

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A. SUMMARY OF DATA AND CALCULATIONS

Computed values for the modulator circuits.

TABLE II

Pulse Repetition Rate	400	2Kc	10Kc
Average Power Out	130 w	130 w	130 w
Pulse Duration	1microsec.	1microsec.	1microsec.
Magnetron	4J31	2J25	2J70
Duty Ratio	.0004	0.002	0.01
Peak Power Out	325kw	65kw	13kw
Magnetron Efficiency	52%	42%	55%
Peak Input Power	624kw	154.6kw	24kw
Peak Magnetron Voltage	22.3kv	11kv	6kv
Peak Magnetron Current	28amps	14.04amps	4amps
Magnetron Resistance	797ohms	783ohms	1500ohms
Pulse Transformer Turns Ratio	3.99	3.96	5.47
Peak Modulator Current	111.8amps	55.6amps	22amps
Average Modulator Current	44.7ma	111.2ma	220ma
Charging Voltage of PFN	11.18kv	5.56kv	2.2kv
Power Supply Voltage	6.21kv	3.09kv	1.22kv
Charging Inductance	63.1h	2.52h	100mh
Average Charging Current	49.6ma	124ma	237ma

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Peak Input Power	624kw	154.6kw	24kw
Peak Magnetron Voltage	22.3kv	11kv	6kv
Peak Magnetron Current	28amps	14.0amps	4amps
Magnetron Resistance	797ohms	783ohms	1500ohms
Pulse Transformer Turns Ratio	3.99	3.96	5.47
Peak Modulator Current	111.8amps	55.6amps	22amps
Average Modulator Current	44.7ma	111.2ma	220ma
Charging Voltage of PFN	11.18kv	5.56kv	2.2kv
Power Supply Voltage	6.21kv	3.09kv	1.22kv
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TABLE III

Component Ratings or Types Selected for the Three Modulators

Component	Modulator: 400	2Kc	10Kc
Charging Reactor	63.1 h	2.52 h	100 mh
Switch Tube	5C22	4C35	5949/1907
Pulse-Forming Network	12E5-1-400-50P2T	6E5-1-2000-50P2T	3E5-1-10000-50P2T
Shunt Diode	3B26	3B26	3B26
Shunt Resistor	1k-10w	1k-10w	1k-10w

TABLE IV

Charging Reactors

Modulator	Size (cu.in.) a	b	c	Weight(#'s)	Cost
400	4.31	5.06	6.46	10.5	$36.00
2Kc	2.625	1.06	4.25	3.0	19.00
10Kc	1.81	1.94	2.75	1.0	14.00

TABLE V

Pulse-Forming Networks

Modulator	Size (cu.in.) a	b	c	Weight(#'s)	Cost
400	2.25	3.75	6.25	2.75	$35.00
2Kc	2.5	3.75	4.875	2.75	35.00
10Kc	3.75	4.56	4.25	4.0	50.00

Size here refers to a rectangular case where a is the length, b is the width, and c is the height over-all.

TABLE III

Component Ratings or Types Selected for the Three Modulators

Component	Modulator 400	2Kc	10Kc
Charging Reactor	63.1 h	2.52 h	100 mh
Switch Tube	5022	4C35	5949/1907
Pulse-Forming Network	12E5-1-400-50P2T	6E5-1-2000-50P2T	3E5-1-10000-50P2T
Shunt Diode	3B26	3B26	3B26
Shunt Resistor	1k-10w	1k-10w	1k-10w

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TABLE VI

Switching Tubes

Modulator	Size (cu.in.) h	d	Weight(#'s)	Cost
400	8.75	2.5	0.59	$42.75
2Kc	6.7	2.5	0.625	33.05
10Kc	12.0	3.06+	1.5+	150.00+
		Shunt Diode		
All	4.2	1.25	0.5	18.00
		Shunt Resistance		
All	2.0	0.468	0.1	.33

Size here refers to a cylindrical volume where d is the outside diameter and h is the over-all height or length.

+ For explanation and alternative see Discussion.

TABLE VI

Switching Tubes

Modulator	Size (cu.in.) h	d	Weight(#'s)	Cost
400	3.75	2.5	0.59	$42.75
2Kc	6.7	2.5	0.625	33.05
10Kc	12.0	3.06+	1.5+	150.00+
		Shunt Diode		
All	4.2	1.25	0.5	18.00
		Shunt Resistance		
All	2.0	0.468	0.1	.33

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B. SAMPLE CALCULATIONS

Refer to Figure IV for the equivalent circuit used in the following analysis. The analysis of the circuit will be made using the 10Kc pulse repetition rate as representative of the calculations necessary.

The magnetron chosen for use at this pulse rate is the 2J70. At this pulse rate the magnetron has the following operating characteristics:

$$E = 6\text{kv}$$

$$I = 4 \text{ amps}$$

$$\text{eff} = 55\%$$

The peak power out is E x I x eff, and in this case is 13kw. The average power is the peak power times the duty ratio. Therefore

$$P_{ave} = P_{peak} \times \text{duty ratio} = P_{peak} \times \tau \times f_r$$

$$P_{ave} = 13 \times 10^3 \times 10^{-6} \times 10^{-4} = 130 \text{ watts}$$

The static resistance of the magnetron is E/I = 6kv/4amps = 1500 ohms. If the pulse transformer has the ratio of the secondary turns to the primary turns equal to 5.5:1, the load will be reflected back to the primary as 50 ohms, which matches the impednace of the coaxial cable. The voltage and current necessary in the primary to provide the proper operating point are

$$E_1 = \frac{6}{5.5} = 1.09 \text{ kv}$$

$$I_1 = 4 \times 5.5 = 22 \text{ amps}$$

$$I_{1ave} = 22 \times .01 = 220 \text{ mamps.}$$

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The equivalent capacitance of the pulse-forming network is given by

$$C = \frac{\tau}{2R_c} = \frac{10^{-6}}{10^{2}} = 10^{-8} \text{ farads}$$

The inductance necessary for d-c resonant charging is

$$L = \frac{1}{\pi^2 f_r^2 C_N} = \frac{1}{\pi^2 \times 10^8 \times 10^{-8}} = 100 \text{ mhenries.}$$

Because we know what the voltage must be across the primary of the pulse transformer, the voltage across the pulse-forming network is also known since it delivers a pulse of amplitude of half the value of the charging voltage. Then

$$E_{st} = 2 \times E_1 = 2 \times 1.09 = 2.18 \text{ kv}$$

When using resonant charging, the pulse- forming network will charge to a value which is between 1.8 and 1.95 times the d-c supply voltage. In the analysis we chose to be conservative and used 1.8

$$E_{bb} = \frac{E_{st}}{1.8} = 2.18\text{kv}/1.8 = 1.21 \text{ kv.}$$

The average charging current is given by

$$I_{ave} = \frac{1}{T_r}\int_0^{T_r} i_{ch}(t)\,dt$$

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$$I_{ave} = \frac{1}{T} \int_0^T i_{ck}(t)\,dt$$

Substitution of the previously calculated values in the integrated expression show that $I_{ave} = 0.237$ amps.

This completes the necessary calculations to determine the circuit parameters and the voltage and current ratings.

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The design engineer of the National Capacitor Company of Quincy, Massachusetts, Mr. W. E. Carlson, furnished the figures for the pulse-forming networks. The charging reactors were designed and the costs estimated by Mr. H. N. French of the Newton Engineering Service in Roxbury, Massachusetts.

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